DESIGN OF AN ADVANCED HEADFORM FOR THE PREDICTION OF EYE AND FACIAL INJURIES

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ABSTRACT

The Virginia Tech – Wake Forest, Center for Injury Biomechanics is in the second year of a multi-year research effort focused on predicting face and eye injury resulting from blunt impacts. The primary thrust of this effort is the development of physical headform capable of measuring face and eye impact loads. In order to assess the capability of protective equipment in reducing eye and facial injuries, the FOCUS headform is being developed with the capability of predicting fracture of facial bones, as well as eye injuries from impact loading. The headform will be used by the United States Army to test and evaluate various protective devices and other equipment to assess the likelihood of these devices to prevent, or possibly cause, an eye or facial injury. It is expected that this headform will be used by researchers and engineers in other disciplines as well; for instance, this headform can be used to evaluate the injury potential of sports equipment or the effectiveness of automotive safety systems.

1. INTRODUCTION

The rate of eye injuries has dramatically increased in warfare from approximately 2% during World War I and World War II, to nearly 13% during Operation Desert Storm (Heier 1993, Wong 2000) (Figure 1). While many of the conflict-related eye injuries are caused by shrapnel and other debris, nearly 25% of the injuries are also caused by blunt trauma from motor-vehicle and helicopter crashes, falling, and direct hits from blunt objects (Mader 1993, Biehl 1999). One reason for the increase in eye injuries in modern day military conflicts is a lack of modernization of protective goggles and face shields to keep up with advances in weaponry (Biehl 1999).

Current anthropometric test device (ATD) headforms lack instrumentation and facial features to allow detailed assessment of eye or discrete facial injuries (Figure 2). The current state-of-the-art ATD headform used for most impact biomechanics testing is the Hybrid-III headform, which is typically instrumented with a tri-axial accelerometer mounted at the center of gravity of the head.

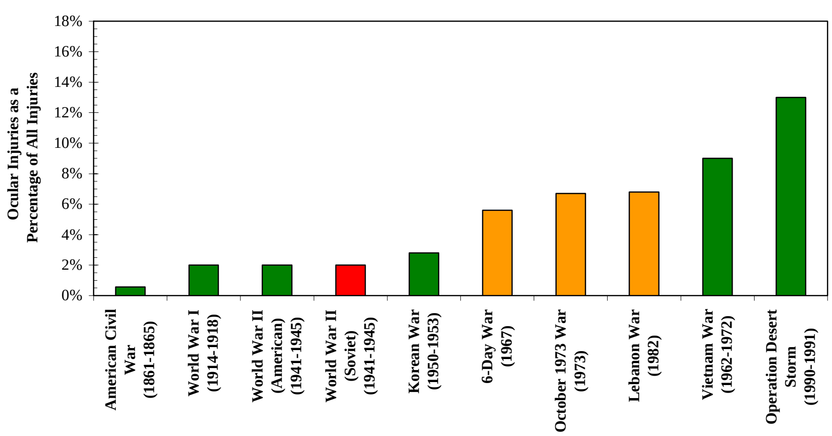

FIGURE 1: Ocular injuries shown as a percentage of total war injuries from 1861 to present.

FIGURE 2: The Hybrid-III headform lacks detailed facial features.

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The resultant linear acceleration of the head center of gravity over time has been used to calculate additional injury measures. The injury criterion most commonly used for head injury assessment is Head Injury Criteria (HIC), which can be used to assess global injuries to the skull and the brain (Eppinger 1999). Although previous research has shown different injury tolerance values for different facial bones, the HIC cannot distinguish between impacts at different regions of the skull; therefore, HIC assumes equal probability of injury for the entire skull. Additionally, because of the limited array of instrumentation, there is no way of detecting any type of impact to the eyes and assess eye injury risk.

Other ATD headforms are used for standards testing of protective goggles and other eye protective equipment. The American National Standards Institute (ANSI) headform was developed from the Hybrid-II ATD. While both the ANSI and the Hybrid-II headforms include details of the eyes, nose, and mouth, the difference between the ANSI headform and the Hybrid-II headform is the detailed ear (Figure 3). The ear allows eye and face protection to be worn correctly on the headform during testing. Although this headform's main application is standards testing of eye and face protection, it is not capable of predicting eye or facial injuries, because it carries no instrumentation. Instead, protective devices are evaluated for pass-fail based on whether there is contact to the eyes or face, as well as inspection of the structural integrity of the protective equipment post-impact.

FIGURE 3: The ANSI headform has the correct anthropometric features for testing eye and face protection, but no instrumentation for measuring impact forces.

In order to assess the capability of protective equipment in reducing eye and facial injuries, a new advanced headform is being developed that can predict fracture of facial bones, as well as eye injury from impact loading. Because of its emphasis on eye and orbital injuries, the name of this new advanced headform will be the FOCUS Headform, which stands for Facial and Ocular CountermeasUre Safety Headform.

2. DEVELOPMENT

The headform is currently being developed at the Virginia Tech – Wake Forest, Center for Injury Biomechanics, in conjunction with Denton ATD, Inc. and input from the United States Army Aeromedical Research Laboratory (USAARL). The headform is currently in development and validation testing.

2.1 Headform Geometry

The exterior geometry of the headform will match the anthropometry of a 50^{th} percentile male soldier, developed by the United States Army Aeromedical Research Laboratory (USAARL) (Figure 4). Anthropometrically accurate features defined by this headform geometry will allow helmets and other headgear to fit more precisely than other current ATD headforms.

FIGURE 4: The USAARL headform models the average US Army soldier facial anthropometry.

The geometry of the USAARL headform was imported into a computer aided design (CAD) program (Figure 5). This geometry served to define the exterior envelope of the FOCUS headform; the internal structures of this headform were then designed to accommodate the specific sensor requirements while maintaining the mass and inertial properties necessary for biofidelic response of the head to impact loading.

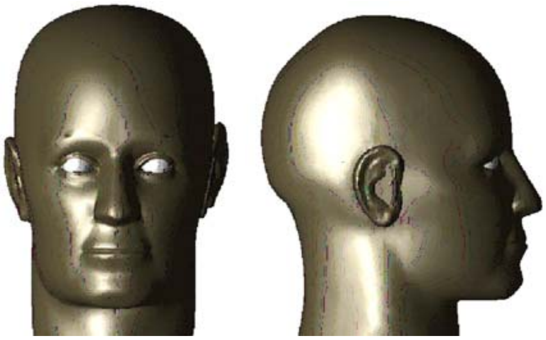

FIGURE 5: The FOCUS headform exterior geometry is modeled after the specified USAARL headform.

2.2 Facial Design and Sensors

In order to assess the severity of blows to various regions of the face, the skull will be segmented into various sensing areas consistent with the anthropometric regions of the human skull. Five facial bones will be monitored for injury with the frontal, zygoma, and maxilla monitored separately on left and right sides, and the nasal and mandible monitored as individual regions with no distinction between left and right sides (Figure 6).

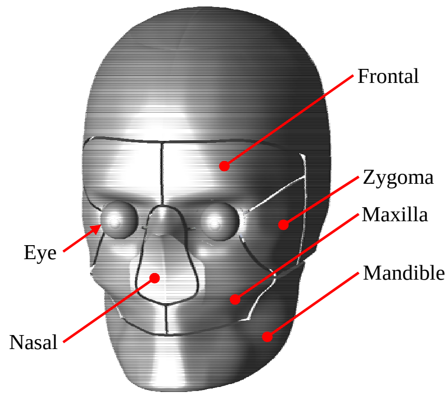

FIGURE 6: Segmentation of instrumented FOCUS headform.

The headform will consist of an outer layer of molded skin, with material properties consistent in thickness and force-deflection response to actual skin, and an underlying rigid skull. Average facial skin thickness was taken from previously published studies of facial skin thickness (Phillips 1996). A visual representation of approximate skin thickness in various locations around the FOCUS headform face is shown (Figure 7).

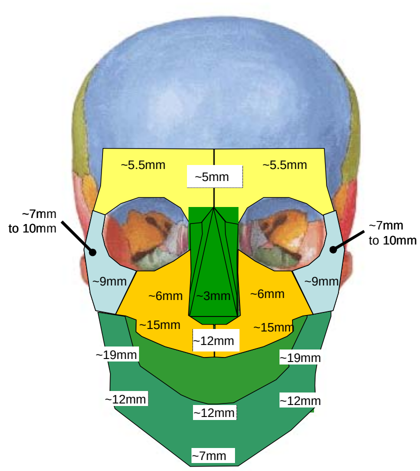

FIGURE 7: Average skin thickness (adapted from Phillips 1996).

2.3 Synthetic Eye Design and Sensors

In addition to the facial segmentation and measurements from facial load cells, the headform will be capable of predicting eye injury risk. This will be done with a modular design capable of testing using a synthetic eye for blunt impacts or a frangible eye for penetrating impacts (Figure 8).

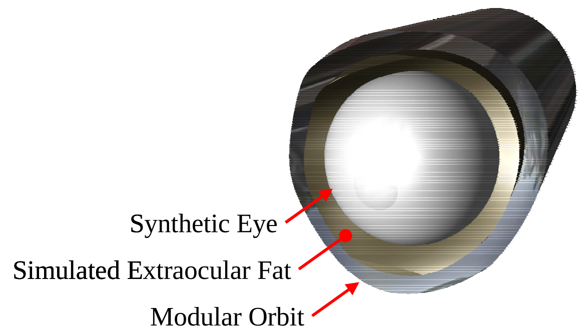

FIGURE 8: Synthetic eye in modular simulated orbit. The synthetic eye and simulated extraocular fat can be removed for use of frangible eyes as well.

The synthetic eye will be a simulated eye that matches as closely as possible the force-deflection characteristics of the human eye *in-situ*. The force-deflection response of the human eye was determined by impact testing of eyes in post-mortem human heads from a parallel study. Eyes were impacted by a spring powered impactor at approximately 10 m/s and the force-deflection corridors for *in-situ* human eyes were determined (Figure 9). Current development efforts include determining the correct material selections to match the force-deflection response of the synthetic eyes to those of the *in-situ* human eyes.

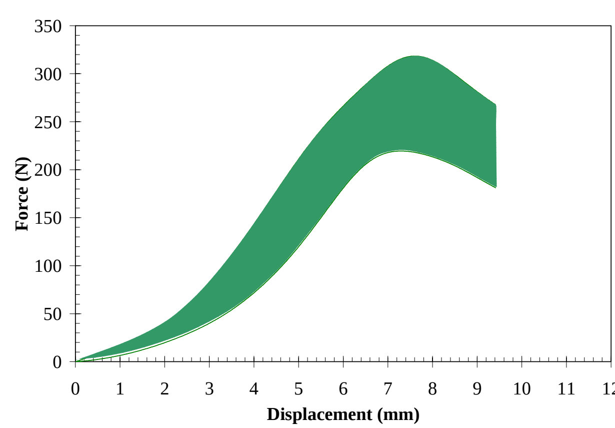

FIGURE 9: Force-deflection curve of human eye in-situ from blunt impact at 10 m/s. The synthetic eye and simulated extraocular fat in the FOCUS headform will match as closely as possible this force-deflection curve.

Due to the modularity of the FOCUS headform design, the orbit of the headform will be a removable mounting cup, which allows a frangible eye to be placed in the headform where penetrating injuries are expected. The frangible eyes will be mounted in the removable orbit using a ballistic gelatin solution, which is commonly used in other eye impact studies (Vinger 1999, Stitzel 2002). Frangible eyes will allow the user to test for penetrating injuries using post-mortem human or porcine eyes, as well as potentially other surrogates.

2.4 Injury Assessment

Each facial bone segment will be monitored by a three-axis load cell capable of detecting loads imparted onto this facial region from any direction. Injuries will be predicted by correlating measured loads from the load cells to known failure limits from previously analyzed impact tests using human cadavers (Hodgson 1967, Melvin 1969, Schneider 1972, Nyquist 1986, Yoganandan 1993, Hopper 1994, Allsop 2001, Viano 2004) (Figure 10). Parametric injury criteria for predicting injury risk from measured impact loads are also being developed to more accurately represent a percent risk of injury vs. a simple injury threshold, which does not account for variations in injury tolerance across the population.

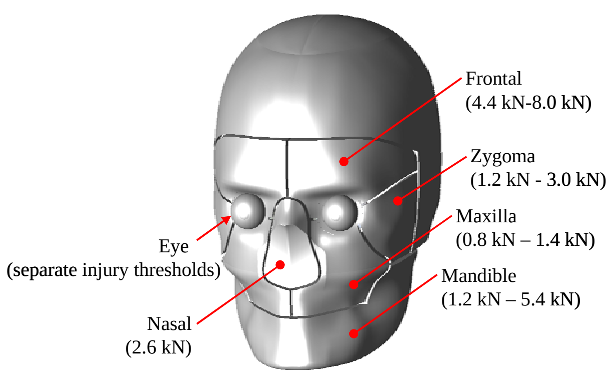

FIGURE 10: Schematic of segmentation of FOCUS headform with reported fracture loads from the literature.

Injury assessment for the synthetic eye will be performed in a similar manner. A uni-axial load cell at the aft-end of the modular orbit will measure impact loads transmitted to the eye and surrounding soft tissue. Eye injury risk functions have been developed based on an extensive database of all eye injury impact tests reported in the literature (Duma 2005, Kennedy 2006). These injury risk functions will serve as the basis for the development of new injury risk criteria that use the load measured in the load cell to predict injury risk of various types of eye injury, including corneal abrasion, hyphema, lens dislocation, retinal damage, and globe rupture (Figure 11).

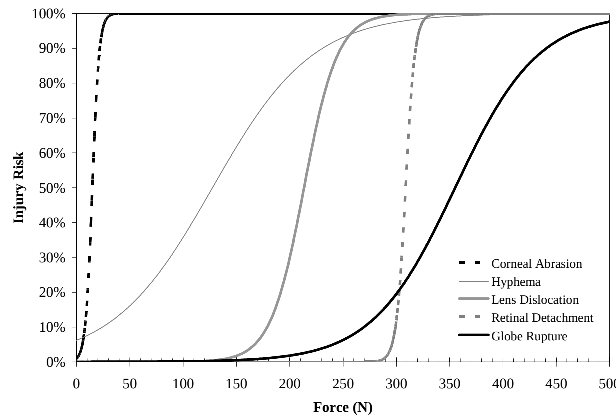

FIGURE 11: Example of parametric injury risk function for eye injuries based on transmitted load, developed from existing eye injury risk functions.
(Note: this figure does not depict the final version of the injury risk functions and should not be used to predict injury risk)

3. TESTING AND VALIDATION

Prior to widespread implementation of the FOCUS headform for assessment of facial and eye injury risk, the advanced ATD head will be tested, evaluated, and injury responses of each of the sensors validated. Each of the discretized facial load cells and the synthetic eyes will be subjected to impact testing with blunt objects and injury risk functions will be verified that known injurious events from cadaver test data are likewise measured to be injurious events by the advanced headform.

3.1 Facial Segment Testing

Validation testing with the facial bone segments of the FOCUS headform will be conducted with impactors of various sizes as used in previous facial bone fracture tests (Hodgson 1967, Melvin 1969, Schneider 1972, Nyquist 1986, Yoganandan 1993, Hopper 1994, Allsop 2001, Viano 2004) (Figure 12). Loads measured by the facial load cell will be correlated to the impactor loads that are reported to cause fracture in post-mortem human subjects. These dose-response measurements will be analyzed to develop defined facial injury criteria for the FOCUS headform.

3.2 Synthetic Eye Testing

Validation testing of the synthetic eye will be accomplished in a similar manner to the validation testing of the facial bone segments. An extensive database of various projectile impacts and their associated eye injury risk will be the basis for validation testing. Eye impact tests will be conducted with various projectiles and at various impact velocities (Figure 13).

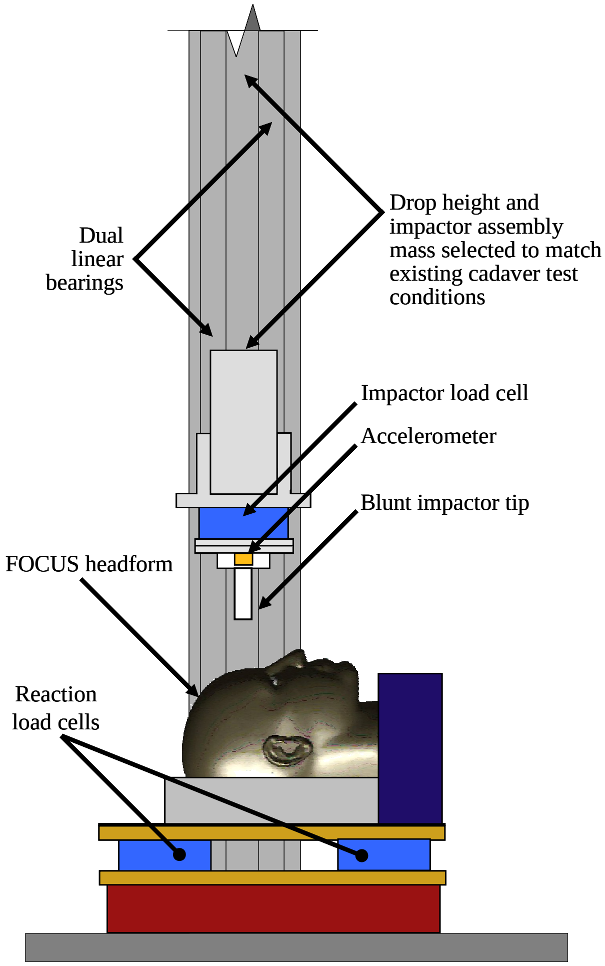

FIGURE 12: Schematic of test setup for facial impact validation tests. The impactor height and tip will be selected to match previously published cadaver test data.

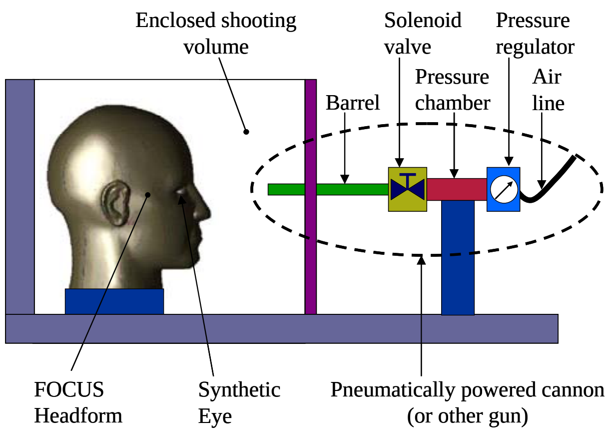

FIGURE 13: Schematic of test setup for eye impact validation tests.

The eye injury risk based upon projectile characteristics of normalized energy (J/m^2) can be calibrated to the force and/or impulse measured by the load cells of the eye. The normalized energy of the projectile is simply the kinetic energy of the projectile divided by the cross-sectional area of the projectile or the cross-sectional area of a spherical projectile (Eq. 1). Similar to the facial load cell testing, the dose-response measurements of the eye impact tests will be analyzed to develop defined eye injury criteria for the FOCUS headform.

$$\text{Normalized Energy}\left(\frac{\text{kg}}{\text{s}^2}\right)=\frac{\text{Kinetic Energy}}{\text{Projected Area}}=\frac{\frac{1}{2}mv^2}{\pi r^2}\text{(for a sphere)} \quad \text{Eq.(1)}$$

3.3 Final Validation

Final validation approval for the headform will be determined based on the headform's ability to distinguish between injurious and non-injurious impact events of both the eye and facial bones. Additionally, the validated FOCUS headform must meet the same biofidelity test requirements for existing ATD headforms, so that not only does it have assessment capabilities that exceed those of the current state-of-the-art headforms, but also that these new capabilities do not come at the expense of current features or biofidelic accuracy.

4. CONCLUSION

The relative severity of both eye and facial injuries is much greater for the military than in the civilian population; however, these injuries in both the civilian and military sectors can be severely debilitating and pose an enormous health cost. Due to a lack of instrumentation, the prediction of eye and facial injuries using anthropomorphic test devices is not currently possible. The current study presents a new technology currently being developed to determine the risk of eye and facial injuries from impacts. The final, validated FOCUS headform will allow for accurate assessment of the effectiveness of goggles, faceshields, and other protective devices for preventing serious eye and facial injuries. It is expected that once fully developed, this technology will be useful not only for the military to evaluate protective equipment prior to deployment, but also will be useful in the civilian population for evaluation of various facial impact scenarios, such as sports injuries and automotive accidents.

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REFERENCES

Allsop DL and Kennett KB. (2001) Skull and facial bone trauma. In Accidental Injury: Biomechanics and Prevention. 2nd ed., Ch. 12. Springer-Verlag, NY.

Biehl JW, Valdez J, Hemady RK, Steidl SM, Bourke DL. (1999) Penetrating eye injury in war. Military Medicine 164(11): 780-784.

Duma SM, Ng TP, Kennedy EA, Stitzel JD, Herring IP, Kuhn F. (2005) Determination of significant parameters for eye injury risk from projectiles. Journal of Trauma 59(4): 960-964.

Eppinger R, Sun E, Bandak F, Haffner M, Khaewpong N, Maltese M. (1999) Development of improved injury criteria for the assessment of advanced automotive restraint systems- II. NHTSA Docket 98-4405-9.

Heier JS, Enzenauer RW, Wintermeyer SF, Delaney M, LaPiana FP. (1993) Ocular injuries and diseases at a combat support hospital in support of Operations Desert Shield and Desert Storm. Archives of Ophthalmology 111: 795-798.

Hodgson VR. (1967) Tolerance of the facial bones to impact. American Journal of Anatomy 120: 113-122.

Hopper RH, McElhaney JH, Myers. (1994) Mandibular and basilar skull fracture tolerance. SAE 942213.

Kennedy EA, Ng TP, McNally C, Stitzel JD, Duma SM (2006) Risk functions for human and porcine eye rupture based on projectile characteristics of blunt objects. Stapp Car Crash Journal 50.

Mader THL, Aragones JV, Chandler AC, Hazlehurst JA, Heier J, Kingham JD, Stein E. (1993) Ocular and ocular adnexal injuries treated by United States military ophthalmologists during Operation Desert Shield and Desert Storm. Ophthalmology 100: 1462-1467.

Melvin JW, Fuller PM, Daniel RP, Pavliscak GM. (1969) Human head and knee tolerance to localized impacts. SAE 690477.

Nyquist GW, Cavanaugh JM, Goldberg SJ, King AI. (1986) Facial impact tolerance and response. 30th Stapp Car Crash Conference. SAE 861896.

Phillips VM and Smuts NA. (1996) Facial reconstruction: utilization of computerized tomography to measure facial tissue thickness in a mixed racial population. Forensic Science International 83: 51-59.

Schneider DC, Nahum AM. (1972) Impact studies of facial bones and skull. 16th Stapp Car Crash Conference. SAE 720965.

Stitzel JD, Duma SM, Cormier JM, Herring IP. (2002) A nonlinear finite element model of the eye with experimental validation for the prediction of globe rupture. Stapp Car Crash Journal 46.

Viano DC, Bir C, Walilko T, Sherman D. (2004) Ballistic impact to the forehead, zygoma, and mandible: comparison of human and frangible dummy face biomechanics. Journal of Trauma 56(6): 1305-1311.

Vinger PF, Duma SM, Crandall JR. (1999) Baseball hardness as a risk factor for eye injuries. Archives of Ophthalmology 117: 354-358.

Wong TY, Smith GS, Lincoln AE, Tielsch JM. (2000) Ocular trauma in the United States Army: hospitalization records from 1985 through 1994. American Journal of Ophthalmology 129(5): 645-650.

Yoganandan N, Pintar F, Reinartz J, Sances AJ. (1993) Human facial tolerance to steering wheel impact: a biomechanical study. Journal of Safety Research 24(2).